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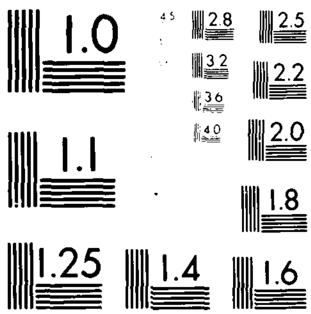

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Technical Report

VISION-PERCEPTION RESEARCH AND ANALYSES RELEVANT TO DISPLAY DESIGN FOR UNDERWATER APPLICATIONS

W. S. Vaughan, Jr.
Oceanautics, Inc.

J. A. S. Kinney
Naval Submarine Medical Research Laboratory

Contract Number: N00014-79-C-0602
Work Unit Number: NR 196-157

Prepared for:

Engineering Psychology Programs
Psychological Sciences Division
Office of Naval Research
Arlington, Virginia 22217

Prepared by:

OCEANAUTICS, Inc.

422 Sixth Street
Annapolis, Maryland 21403

November 1980

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20. ABSTRACT (Continue on reverse side if necessary and identify by block number)

This report is a review of vision research results and analyses which bear on five common decisions in display design for underwater applications: eye-to-console distance, symbol size, display luminance, peripheral location, and use of color. The material is intended as a database of research documentation supporting a designer guide of recommendations for general classes of underwater system applications such as displays for vehicle consoles -

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and hand-held equipments, painting and illuminating underwater structures.

Each of the five display design issues is discussed from the viewpoint of the visual/perceptual phenomena which occur underwater and are of consequence to optimizing design solutions. The discussions emphasize the differences between air and water viewing environments, and give particular attention to the problem of turbidity as a determiner of effective display design.

TABLE OF CONTENTS

TABLE OF CONTENTS (Continued)

LIST OF FIGURES

LIST OF TABLES

ACKNOWLEDGMENTS

This work was supported jointly by the Office of Naval Research, Naval Medical Research and Development Command, and Naval Sea Systems Command. We are particularly indebted to Dr. Martin A. Tolcott and Mr. Gerald S. Malecki of ONR, CAPT James Vorosmarti and CDR Robert Biersner of NMR&D and CDR Robert Smith of NAVSEA for their guidance and encouragement.

VISION-PERCEPTION RESEARCH AND ANALYSES RELEVANT TO DISPLAY DESIGN FOR UNDERWATER APPLICATIONS

I. INTRODUCTION

A variety of underwater vehicles and work systems, life support and hand-held equipments are being designed to broaden the range of man's productive activity undersea. System effectiveness and diver safety are becoming increasingly dependent on information transfer via visual displays, and yet displays are not optimized for the unique conditions of underwater viewing environments. Water absorbs light energy, and particles suspended in the water scatter light. Both phenomena are wavelength selective, and so the amount of energy is reduced and its spectral composition modified over relatively short pathways. Light rays eventually reach the diver's eyes by passing through a water/air interface at the faceplate which optically distorts the visual image in size, distance and shape.

Human factors guidebooks to display design are applicable to air viewing environments exclusively (Woodson and Conover, 1966; Meister and Sullivan, 1969; Grether and Baker, 1972; Heglin, 1973; Shurtleff, 1980); Military Standard 1472B, Human Engineering Design Criteria for Military Systems, does not include applications to underwater systems. Research on underwater vision and perception has been directed to basic visual processes, and literature reviews integrate research results in terms of basic processes such as resolution and stereoacuity (Luria and Kinney, 1970; Adolfson and Berghage, 1974; Shilling, Werts and Schandelmeier, 1976). Human factor handbooks ignore underwater system applications, and the underwater vision research literature is not targeted to display design issues.

The present work is an effort at bridging the gap between research findings and engineering applications in the area of visual displays for underwater systems. The strategy is to compile, organize and interpret research in vision according to fundamental issues in display design, and then to distill from this database, design recommendations for selected applications such as vehicle consoles and hand-held equipments. This report is the database; a forthcoming report will present design recommendations (Vaughan and Kinney (in press)).

Adolfson, J.A., and Berghage, T. E. Perception and performance under water. New York: John Wiley and Sons, 1974.

Grether, W. F., and Baker, C. A. Visual presentation of information. In H. P. VanCott and R. G. Kinkade (Eds.) Human engineering guide to equipment design. American Institutes for Research, Washington, D.C., 1972.

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II. DATABASE OF VISION-PERCEPTION RESEARCH RELEVANT TO DISPLAY DESIGN ISSUES

A. Eye-to-Console Distance

1. Human Factor Considerations

Traditional vehicles and work stations used in air environments are designed so that the operator's seating arrangement provides 28-30 inches of distance to the display console. This arrangement is based on arm length; enabling operators with shorter than normal arms (5th percentile) to reach controls on the console. Console display characteristics such as size and luminance are optimized for this distance.

Eye-to-console distance in most underwater system applications must be closer than the design standard for systems which operate in air. Except for the deep oceans, most operational environments are turbid to some degree; inshore rivers, harbors and bays are very turbid, and turbidity so seriously attenuates light energy by scattering that consoles must be very close to the diver's eyes in order for displays to be legible. For underwater applications the key human factor consideration is accommodation; the capacity of the eyes to focus close-in objects. In order to overcome the attenuation of light energy by turbid water, display consoles need to be as close to the diver's eyes as he can maintain focus without fatigue.

2. Review of Research and Analyses

a. Accommodation and Age. Younger eyes have better accommodative capacity than older eyes; the deterioration with aging is particularly marked in persons older than 40 years of age. Several studies have been conducted to determine the relationship between age and the capacity to focus close objects (Knox and Ellerbrock, 1950; Borish, 1970). Figure A.1 is an age vs accommodation function which is typical of research findings.

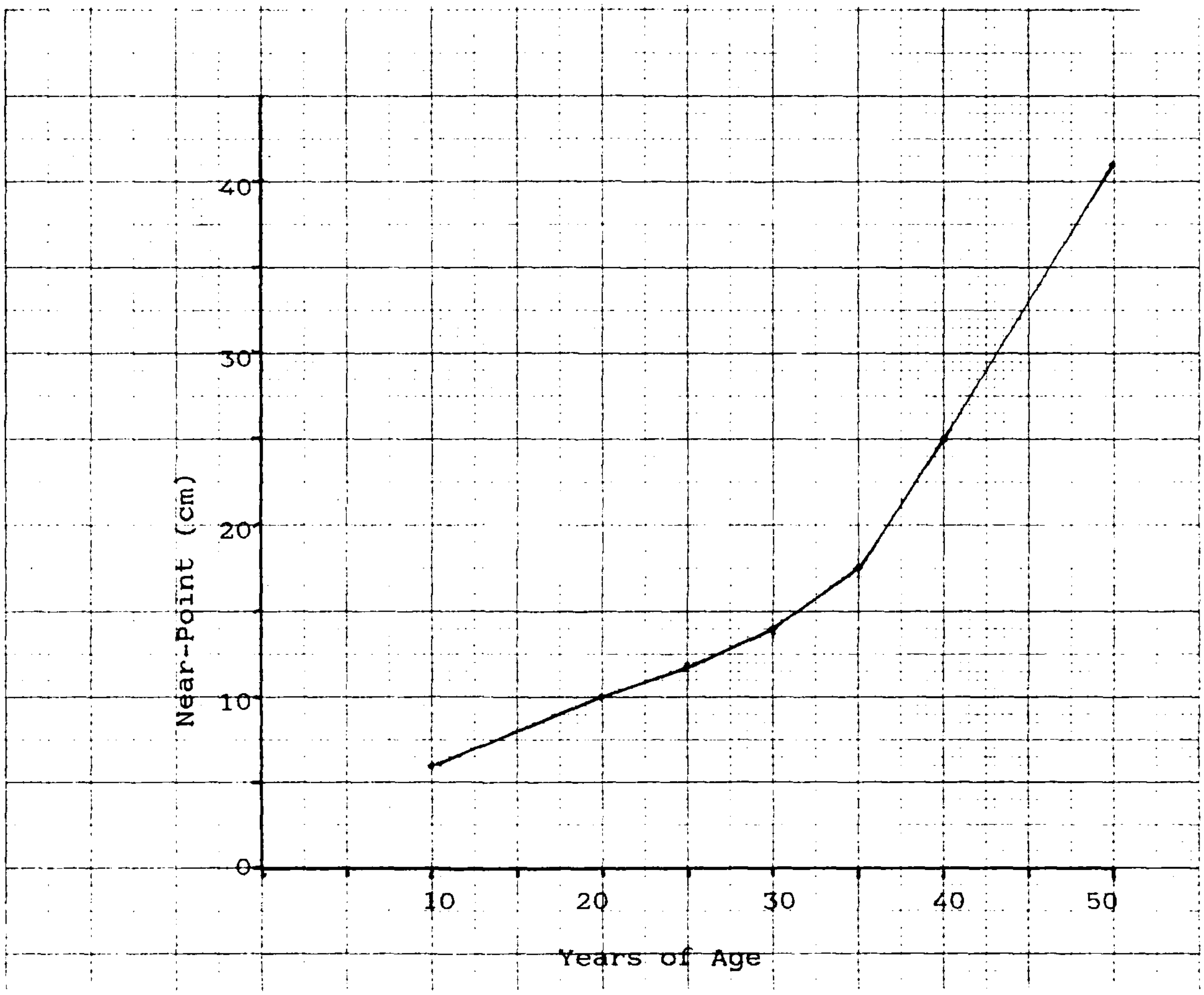

Figure A.1. Accommodation Near-Point (cm) As A Function of Age

In Figure A.1 accommodative capacity is represented by a measured near-point, i.e., that distance which is as close to the eyes as possible without blurring of the object, words, or other visual stimulus. Accommodation is often described by a derived unit, diopters. A diopter is the reciprocal of the near-point as measured in meters. Figure A.2 is included to show the relationship between measured near-point and diopters.

b. Eye-to-Console Distance and Eye Fatigue. There is a rule of thumb in optometric practice that says in order to have clear and comfortable vision, an individual should have to use no more than half of his accommodation in sustained reading or close work (Knox and Ellerbrock, 1950; Borish, 1970; Grosvenor, 1979). This means that an individual who had 5 diopters of accommodation (D = 1/dist (meters)) should use only 2.5 D of it or should not work for long periods of time at 40 cm (.4 m) or closer, without additional correction.

The formula for applying the optometrists rule of thumb is:

$$\text{Limit to Close-In Viewing Distance (m)} = \frac{1}{.5\ D}$$

or, more simply, twice the measured near-point in meters. Table A.1 presents the application of the above formula for five age categories between 20 and 40 years.

Table A.1. Calculations for Limits to Fatigue-Free, Sustained Visual Monitoring

Age	**Accommodation Near-Point (m)**	**Diopters 1/Near-Point (m)**	**.5D**	**Rule of Thumb for Sustained Close-In Visual Work: Distance (m) = $\frac{1}{.5D}$**
40	.25	4.0	2.0	.50 m
35	.18	5.6	2.8	.35 m
30	.14	7.0	3.5	.30 m
25	.12	8.5	4.25	.25 m
20	.10	10.0	5.0	.20 m

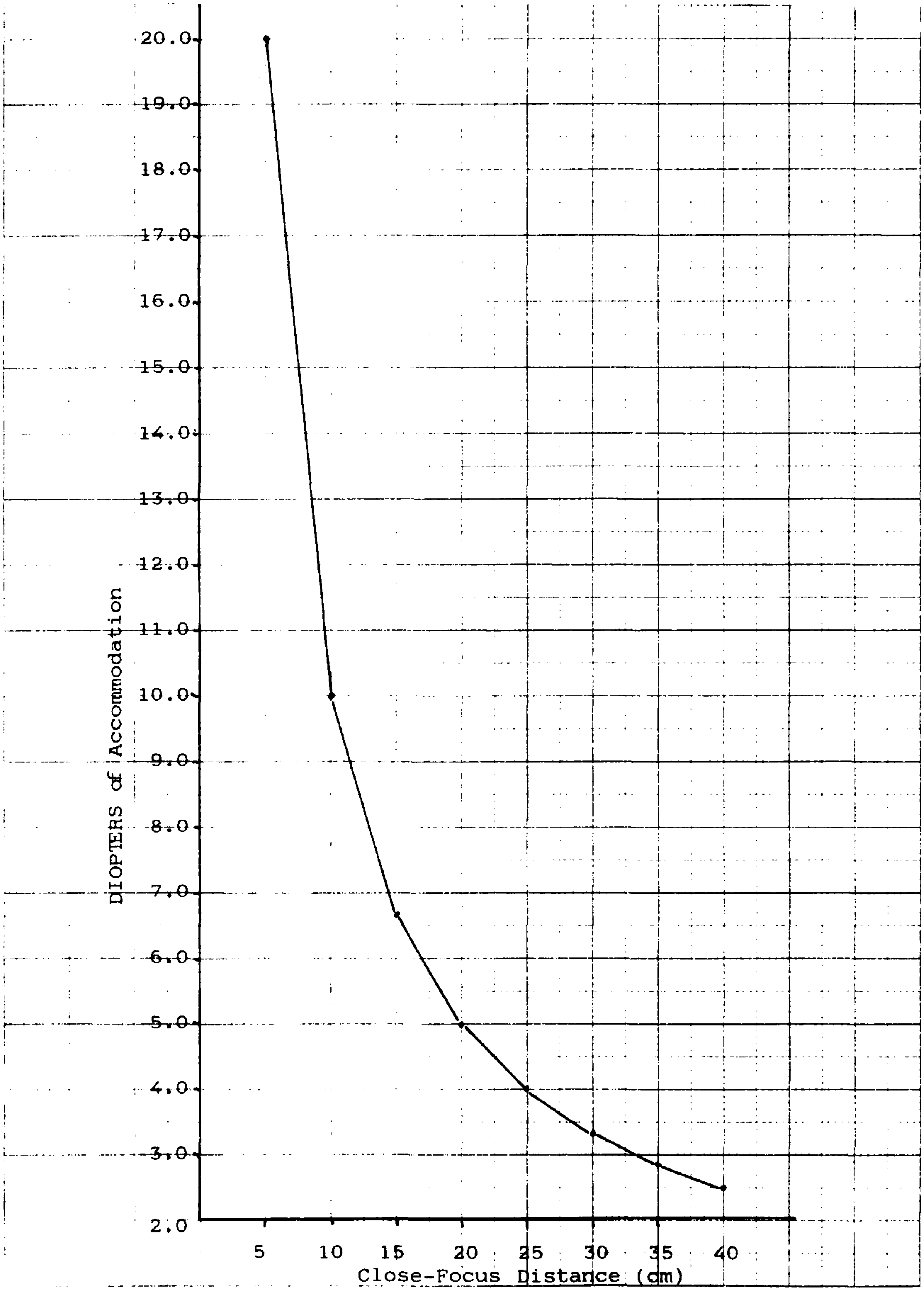

Figure A.2. The Relationship Between Close-In Focussing Distance and Diopters of Accommodation

Although complaints of fatigue or visual fatigue are common among individuals doing close work, attempts to localize the cause of such complaints within the visual system have not been successful. The physiological fatigue of muscle, nerve fibers or of synapses is scarcely ever reached and the accommodative mechanism continues to function perfectly despite prolonged use. Furthermore, there are many studies that show no performance decrement after 6 hours or so of close work (Weber, 1950; Deese, 1957).

In fact, Alpern, 1971, states that if only a part (like 1/2) of accommodative amplitude is used it should be hard to show a decrement with continued practice and indeed it is. Many studies have tried to find evidence of fatigue from too much close work but have failed to do so. In one Herculean study, Weber, 1950, tested a dozen or so visual functions, during an eight-hour day of close work. Nothing changed except for a slight decrease in the ability to accommodate. This did not occur in all subjects; furthermore, it did occur only when they were forced to use maximum accommodative effort. Weber states that it was less common in the younger individuals. Also, decrements over time can be shown in asthenopic patients; i.e., those who complain of eye strain, headaches, etc. (Berens and Sells, 1950).

Thus, the optometric practice of leaving 1/2 of the amplitude of accommodation in reserve appears to be primarily a safety device, and, if the rule is followed, it should mean that all men should be able to watch a display for hours without ill-effects.

c. Eye-to-Console Distance and Peripheral Visual Functions. Accommodation capability of the divers' eyes and the use of 'rule of thumb' to hedge against eye fatigue establish the close-in limit for eye-to-console distance. Outer limit for this distance is determined by display luminance, particularly in turbid water applications where the source luminance is so quickly reduced by

scattering in the pathway to the diver's eyes. To be legible in turbid waters, self-luminous displays need to be very intense even when they are centrally located; i.e., in direct line of sight. Displays located off-axis must penetrate a greater distance and so must be of even greater luminance than displays in the direct line-of-sight. For example, the difference between a 14-inch and an 18-inch eye-to-console distance has a marked effect on peripheral legibility when source luminance is a fixed value. Figure A.3 shows the effect of eye-to-console distance and the legibility of peripherally located displays when source luminance was 342.6 cd/m^2 (Vaughan, Glass and Williams, 1978).

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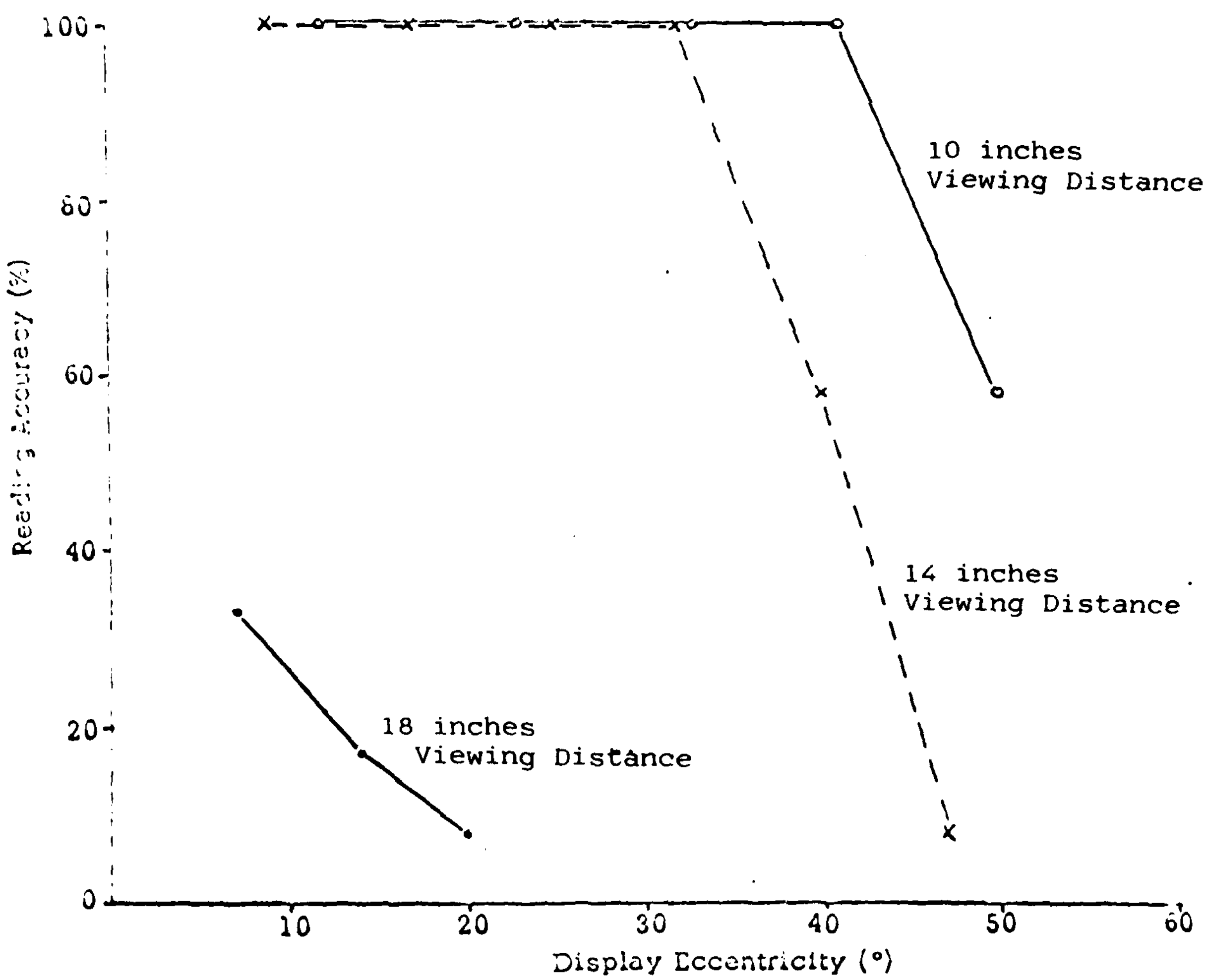

Figure A.3. Legibility of Peripherally Located Displays As A Function of Eye-to-Console Distance (from Vaughan, Glass and Williams, 1978)

B. Symbol Size

1. Human Factor Considerations

Human factor guidebooks are directed to the design of systems which operate in normal air environments; they tend to recommend small-sized symbols in the range 10-20 minutes visual angle for 'good' viewing conditions and large-sized symbols in the range 30-40 minutes visual angle for 'poor' conditions, (Woodson and Conover, 1966; Grether and Baker, 1972; Shurtleff, 1980). Differences in recommended symbol size are intended to compensate for differences in ambient illumination and contrast; larger symbols when ambient luminance is low (less than 3.4 cd/m^2) and the symbol-to-background contrast ratio is small (.10 or less). The current military standard for transilluminated or self-luminous symbols for console applications is a minimum size of 15 minutes visual angle (MIL STD 1472B).

In underwater applications, these recommendations are adequate only for very clear waters, i.e., open oceans. Because of the optical magnification effect of vision through a faceplate in clear water, display symbols could be 75% of the recommended sizes for air applications (Kent and Weissman, 1966). Most operational waters, however, are turbid to some degree, and the scattering effects of suspended particles reduce luminance contrast to an extent which outweighs the potential advantage of optical magnification (Kinney, et al, 1969; Luria, et al, 1967). Also, as the number of particles suspended in the visual pathway is increased (i.e., the water is more turbid), scattering effects progressively reduce the amount of energy delivered to the eyes. Consequently, transilluminated or self-luminous displays need to be larger and more luminous for underwater applications than for air environments.

2. Review of Research and Analyses

Within limits, displays can be made equally legible by various combinations of size and luminance, i.e., small-sized displays of high luminance are as legible as large-sized displays

of low luminance. The contribution of display size in these combinations diminishes as size increases. For example, in air viewing environments, area x luminance is a constant for small-area stimuli (Ricco's Law); at intermediate sizes, the square root of area x luminance is a constant (Piper's Law); at large sizes, visual threshold depends only on luminance (Bartlett, 1965).

The size x luminance interaction was examined for the underwater application using threshold legibility data collected for two display sizes and two conditions of water turbidity: coastal ocean and bay waters (Vaughan, et al, 1977). Figure B.1 is a plot of threshold luminance as calculated at the eye vs visual angle of the display in the range 20-140 minutes of arc. The general shape of these luminance x size functions suggest the following conclusions:

- There is some small display size where an underwater display will be illegible regardless of its luminance.
- There is some low value of luminance where the underwater display will be illegible regardless of its size.
- There is a range of display sizes for which changes in luminance can compensate for changes in size.

Only a very few studies have been conducted under controlled conditions of water turbidity which provide quantitative description of the size x luminance phenomena underwater (Vaughan, et al, 1977, 1978 and 1979).

Figure B.2 illustrates the diminishing contribution of size relative to luminance as the turbidity of the water increases. Sizes 4- and 8-mm digits were viewed in water of varying degrees of turbidity simulating coastal ocean, bay and harbor.

Figure B.3 presents specific size-luminance combinations which yield equivalent, clear legibility under various conditions of underwater viewing. The data include a size range of 20-80 minutes visual angle, dark vs illuminated water and ocean vs harbor turbidity.

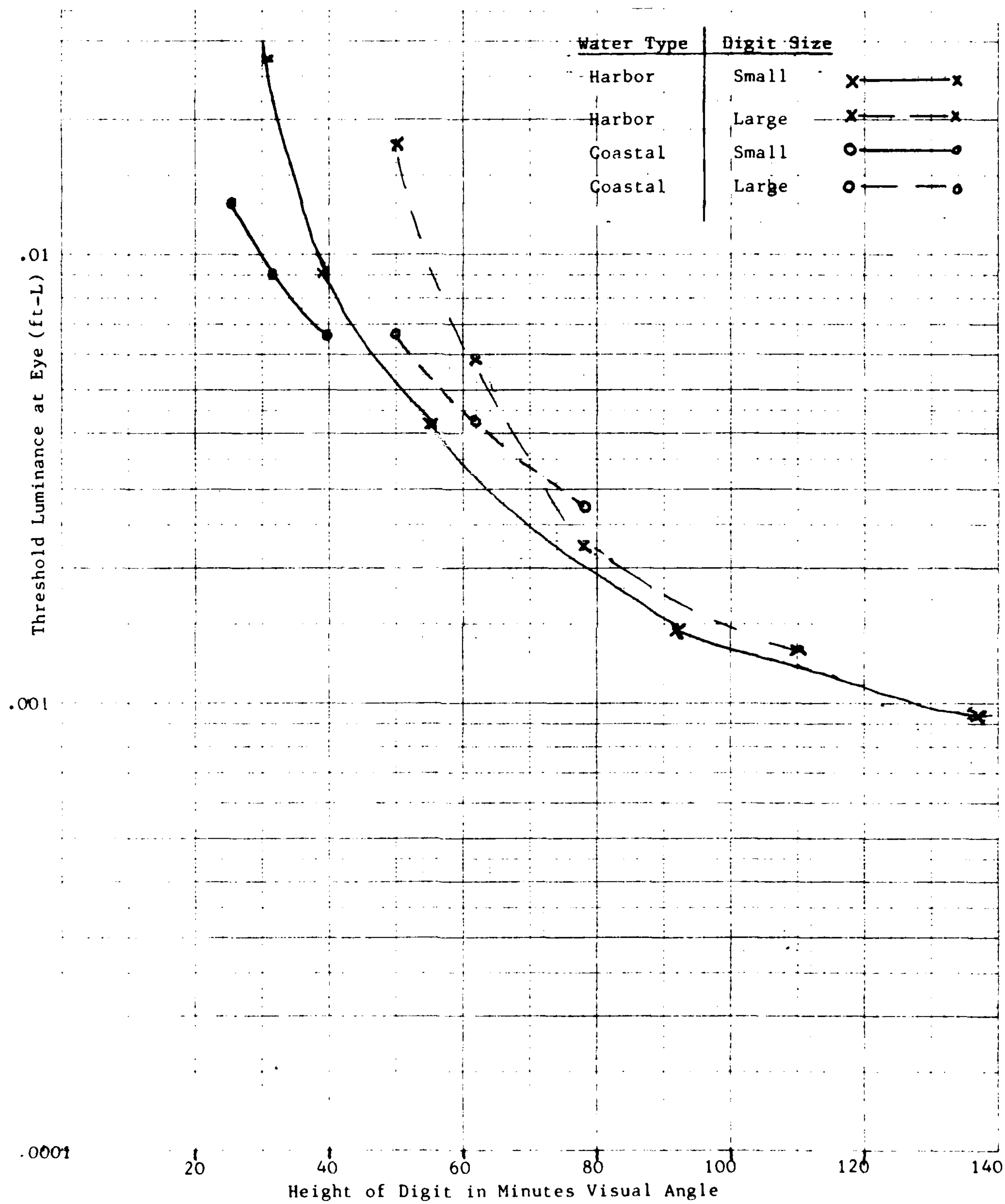

Figure B.1. Luminance Thresholds At the Eye vs Digit Size

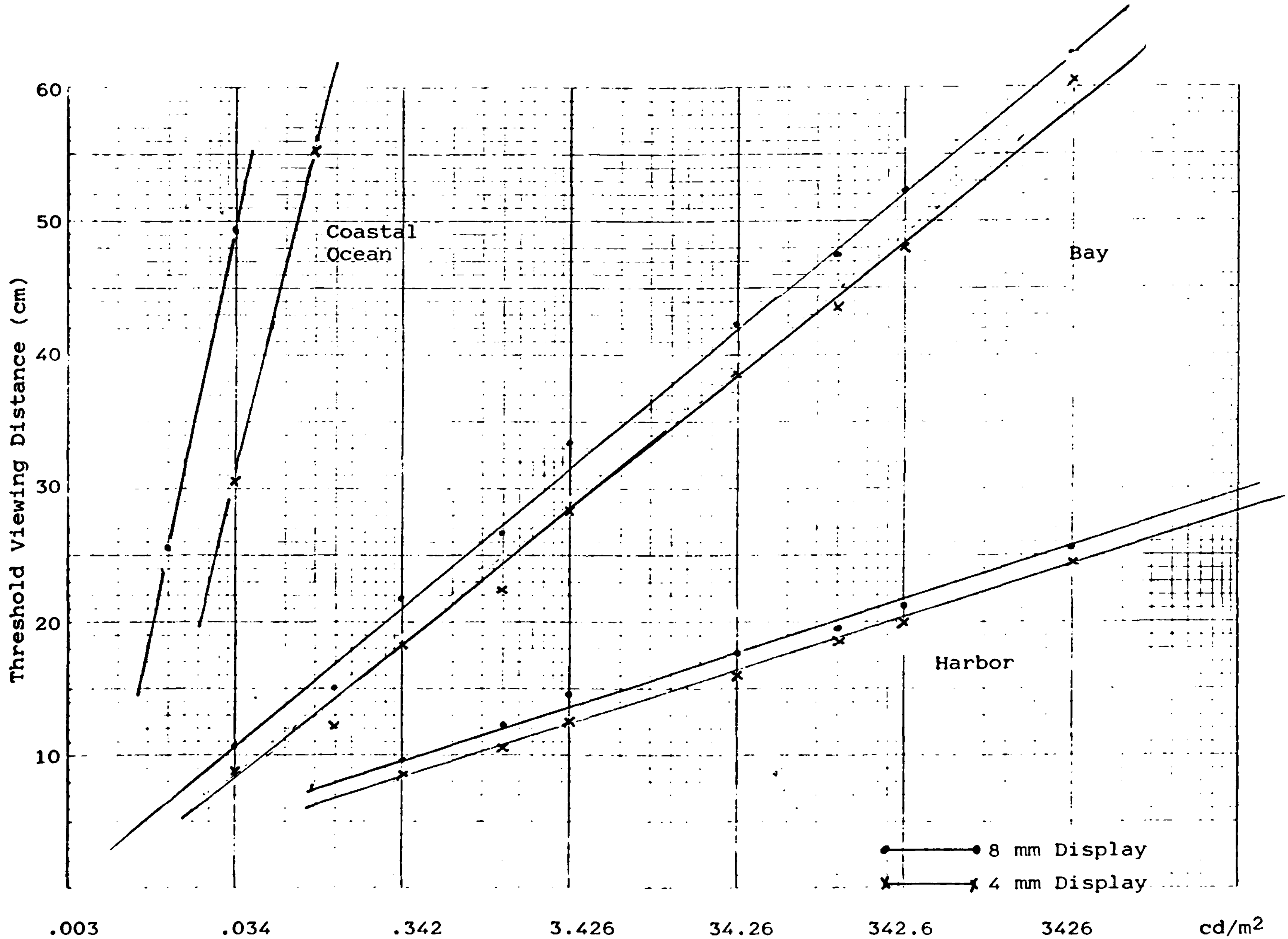

Figure B.2. Effects of Display Size and Luminance in Different Turbidity Conditions

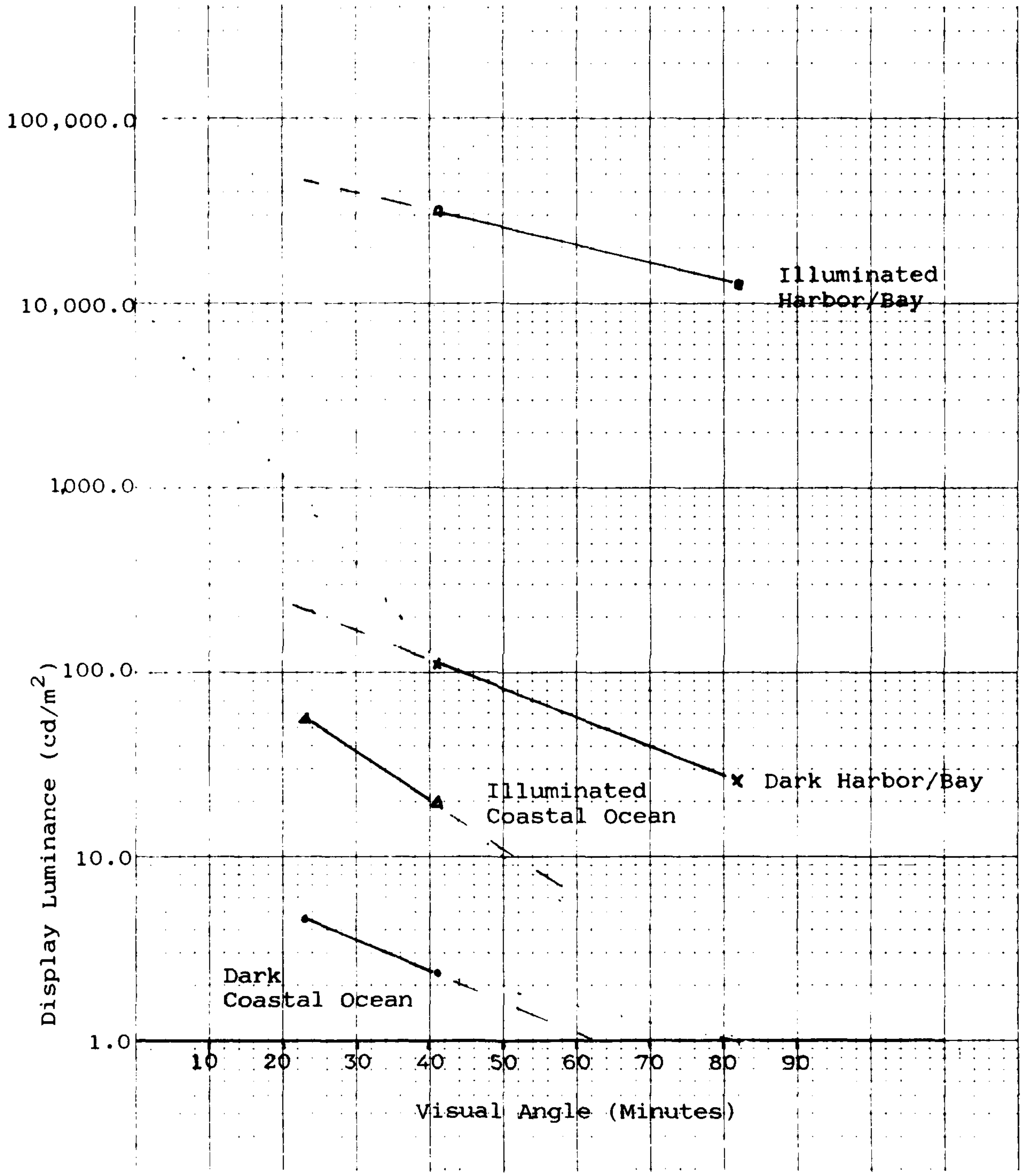

Figure B.3. Display Luminance (cd/m^2) x Size Combinations Required for Clear Legibility in Various Underwater Environments

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C. Display Luminance

1. Human Factor Considerations

a. Luminance Is the Measure of Light Energy Appropriate to Vision. Intensity and luminance* are both properties of light sources, intensity being the appropriate measure for point sources and luminance for extended sources. Intensity is measured in candelas per steradian and luminance in candelas per steradian per unit area. Thus, if viewed as only physical quantities, a simple mathematical conversion is made between them: intensity divided by the effective area of the source yields the luminance.

However, if viewed as stimuli for vision, the apparent simplicity disappears. The proper quantity for assessing the stimulus for vision is the amount of light at the eye. There are a number of different units by which the amount of light at the eye can be assessed; an extremely common one, used in most research relating visual function to amount of light, is luminance. The reason luminance is used rather than intensity is that the amount of illuminance provided at the eye by an extended source does not vary with the distance of the observer, but for a point source it does. Thus one can measure the luminance of the source and not have to worry about how far away the observer is; it will provide the same stimulus at the eye.

This stems simply from the geometry of the situation. The illuminance from a point source decreases with the square of the distance that the receiver is away from the source. With an extended source, however, this decrease is exactly compensated for by having a large area contributing to the receiver.**

*The Hewlett-Packard Optoelectronics Applications Manual uses the words 'sterance' or 'luminous sterance' for luminance. These are not terms in common usage. The accepted term by both the Illum. Engr. Soc. and the International Commission on Illumination (CIE) is luminance.

**This discussion assumes extended sources of light normal to the direction of light propogation. If the source is tilted the definition of luminance must refer to the projected area of the surface (Hardesty and Projector, 1973).

Light emitting diode (LED) displays and miniature lamps, both incandescent and solid state, are typically described by an intensity measure: millicandelas (mcd) or microcandelas (μcd) in the case of LEDs; mean spherical candle power (mscp) in the case of miniature lamps. At the short distances involved in reading displays underwater, these devices are more like extended sources and the proper measure for predicting legibility is luminance.

- <u>LED Conversion</u>

Technical manuals commonly list specifications for LEDs in terms of microcandelas (μcd). This is a unit of candle power, one cd divided by 10^6 or 10^{-6}cd. In order to convert to luminance measures, (cd per unit area), one must divide by the area of the source. While it is difficult to measure the area of the source for LEDs, since they are so small, some manufacturers' technical manuals give this information. Since the area is commonly measured in square millimeters (mm^2) and since one mm^2 is equal to 10^{-6} meter^2, the two 10^{-6} cancel to convert directly to luminance in cd/m^2.

Example:

The catalogue lists intensity as 1430 μcd and the apparent emitting area as 1.7 mm^2

$$\frac{1430 \times 10^{-6} \text{ cd}}{1.7 \times 10^{-6} \text{m}^2} = 841 \text{ cd/m}^2$$

• Miniature Lamp Conversion

Manufacturers' catalogues define the intensity of a given lamp in units of mean spherical candlepower (mscp). This is a measure of the average candlepower of a surface in all directions. It is equal to the total luminance flux (lumens) divided by the surface of a sphere ($4\pi r^2$). In order to convert mscp to luminance first multiply by 10^6 in order to obtain microcandelas, then divide by the apparent emitting area as in the LED conversion. Since the lamp will appear on the display console as a circle of light, use the area of the circle πr^2 as the divider: i.e.,

$$cd/m^2 = \frac{mscp \times 10^6}{\pi r^2}$$

b. Luminance At the Eye Is the Design Objective. Manufacturers' catalogues describe the 'brightness' of their displays as measured at the source; but what determines legibility is the amount of energy that reaches the eye. In air environments where there are no suspended particles of consequence, the difference between source luminance and at-the-eye luminance is trivial; the luminance value in the catalogue is the value that will impact the retina. In typical underwater applications, the water is turbid to some degree; in inshore water environments, very turbid. Turbidity attentuates the source energy and so the designer's task is to select a display element whose known source luminance will be adequate to travel the required distance through the more or less turbid water, and deliver an amount of luminance at the eyes which the diver can see plainly.

2. Review of Research and Analyses

The amount of luminance at the eye required for legibility varies slightly with the area of the retina stimulated, i.e., the visual angle; large-sized stimuli require less luminance than small-sized stimuli for equivalent legibility. Results of experiments on display legibility underwater were analyzed in order to

generate a luminance at the eye vs symbol size function (Vaughan, Glass and Williams, 1978 and 1979). Legibility data were obtained for self-luminous digits of various sizes and colors, at various viewing distances in turbid water viewing environments. Luminance at the eye was calculated from the attenuation coefficients of the turbid water samples for all combinations of display variables and plotted against display size. Figure C.1 shows this function for digits between 20 and 80 minutes visual angle. Luminance required for clear legibility ranged from 3.3 cd/m^2 for a digit size of 20' to 0.5 cd/m^2 for a digit size of 80' visual angle.

Figure C.1 provides a value of luminance at the eye as a design objective. The designer's problem is to determine the amount of source luminance that will deliver at least that much energy to the eye given the attenuation characteristics of the water. This section provides a series of steps for solving the problem in two cases: Case A where the display is to be read in the dark; and Case B where the display is to be read against a background of illuminated water.

Case A: Where the Display Will be Viewed in Dark Water

Step 1: Calculate the visual angle of the display

Since luminance required at the eye for clear legibility varies with visual angle, estimate the viewing distance or use 14 inches as a typical value. Look up in the catalogue or measure the symbol height and apply the formula:

$$\theta' = \frac{(57.3)\ (60)\ h}{d}$$

Step 2: Look-up the amount of luminance at-the-eye required for clear legibility

Table C.1 lists values of luminance for selected values of display visual angle between 20' and 80'. If more precise values of luminance are necessary refer to Figure C.1. Use of either aid provides a target value of luminance for a clearly legible character of known size and viewing distance.

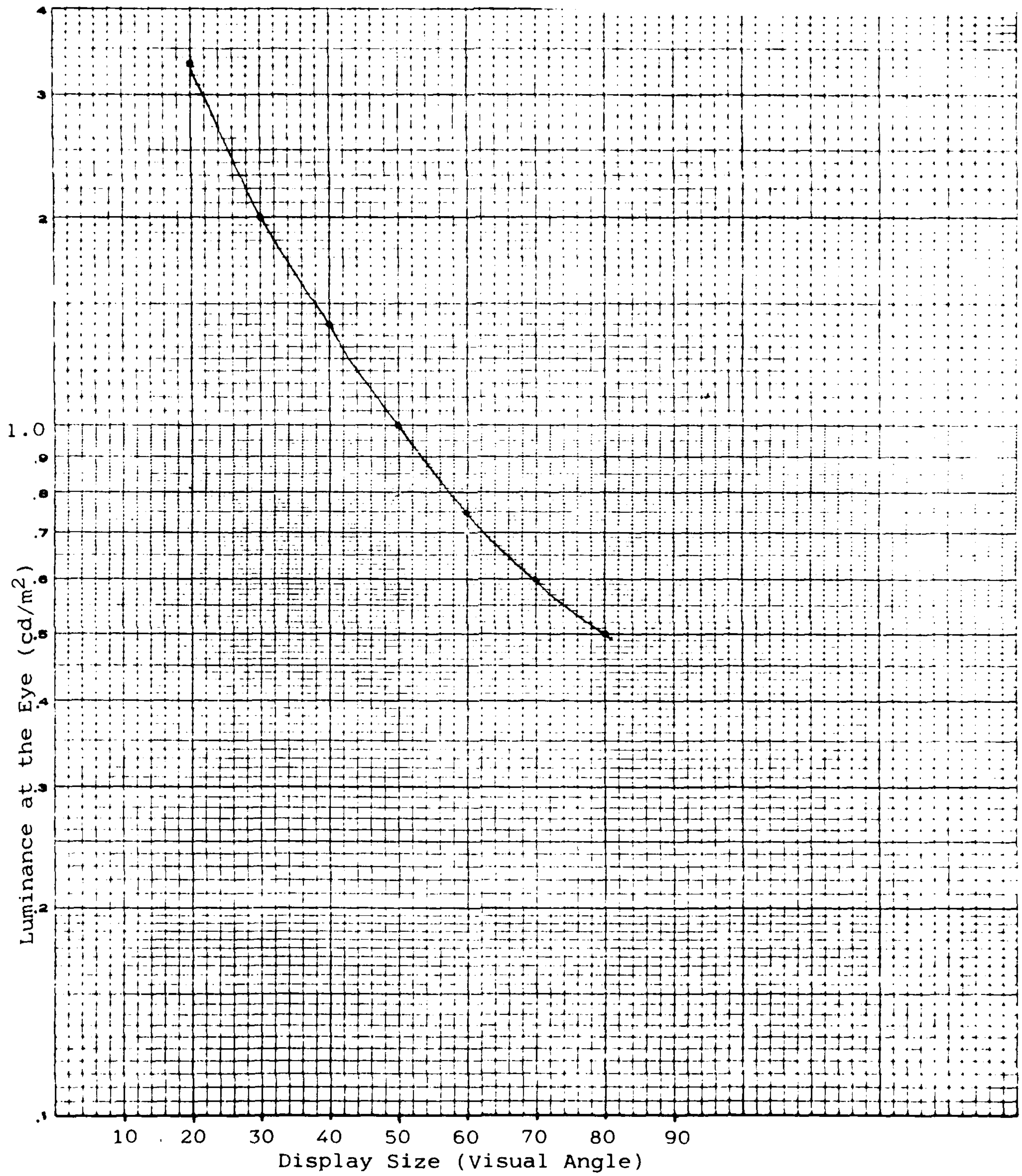

Figure C.1. Luminance Required At the Eye for Clear Legibility As A Function of Display Size

Table C.1. Amounts of Luminance Required At the Eye for A Clearly Legible Alphanumeric Display Against A Dark Background

Visual Angle of the Symbol	Required Luminance (cd/m) at the Eyes
20'	3.30
30'	2.00
40'	1.40
50'	1.00
60'	.75
70'	.60
80'	.50

Step 3: Calculate the transmission (T) value of the water type, display color, viewing distance combination

Water attenuates radiant power or light with the amount of attenuation given by the formula:

$$p = p_o e^{-d\alpha}$$

where

p = radiant power reaching at given distance

p_o = radiant power at the original point

e = base of natural log system (2.718)

d = distance

α = attenuation coefficient which includes both absorption and scatter (usually expressed in natural log units per meter)

Since

$$\text{Transmission} = \frac{P}{P_o}$$

the amount of light transmitted by any given distance of water is given by:

$$T = e^{-d\alpha}$$

The attenuation coefficient (α) is highly specific to a water sample, but gross approximations distinguish major categories of water. Table C.2 lists α values typical of four categories of water for three colors of light. When the water type (and, therefore, α) display color and viewing distance are known, the formula $T = e^{-d\alpha}$ can be applied. Table C.3 lists T values for a range of applications.

Table C.2. Attenuation Coefficients for Green, White and Red Light in Major Classes of Natural Waters

Water Type	Display Color		
	Green	White	Red
Clear Ocean	.10	.10	.30
Coastal Ocean	1.0	1.0	1.5
Bay	3.5	2.5	2.0
Harbor	18.0	16.0	15.0

Table C.3. Proportion of Source Light Transmitted (T)

Water Type	Display Color and Viewing Distances								
	Green			White			Red		
	25 cm	35 cm	45 cm	25 cm	35 cm	45 cm	25 cm	35 cm	45 cm
Clear Ocean	.98	.97	.96	.98	.97	.96	.92	.90	.87
Coastal Ocean	.78	.70	.64	.78	.70	.64	.70	.60	.50
Bay	.42	.30	.20	.54	.42	.32	.60	.50	.40
Harbor	.01	.002	.0003	.02	.004	.0007	.04	.005	.001

Step 4: Calculate display source luminance required for clear legibility

Divide the value of luminance required at the eye (Step 2) by the T value for the viewing conditions (Step 3) to yield luminance required at the source.

$$L_S = \frac{L_E}{T}$$

Table C.4 lists some representative source luminance requirements for typical viewing conditions.

Table C.4. Display Luminance (cd/m^2) Required for Clear Legibility in Dark Waters At 45 cm (18 Inches) Viewing Distance

	Display Color and Size (Visual Angle)								
	Green Display			White Display			Red Display		
	20'	40'	80'	20'	40'	80'	20'	40'	80'
Clear Ocean	3.4	1.5	.5	3.4	1.5	.5	3.8	1.6	.6
Coastal Ocean	5.2	2.2	.8	5.2	2.2	.8	6.6	2.8	1.0
Bay	16.5	7.0	2.5	10.3	4.4	1.6	8.3	3.5	1.3
Harbor	11,000	4,667	1,667	4,714	2,000	715	3,300	1,400	500

Case B: Where the Display Will be Viewed in Illuminated Water

When the application includes a condition of ambient illumination, e.g., shallow water during daylight, then luminance contrast determines legibility not absolute luminance as in Case A. Therefore, the target value, luminance at the eye is calculated from a formula for contrast ratio:

$$CR = \frac{L_E - L_B}{L_B}$$

Contrast ratio must be higher at low ambient light levels than at high ambient levels. Data from one experiment were used to determine these ratios: .40 for low ambient light levels (less than 34 cd/m^2) and .20 for ambient luminances 340 cd/m^2 and greater (Vaughan, Glass and Williams, 1979).

Step 1: Measure/estimate the luminance of the water at the diver's depth

Ambient luminance surrounding a diver will depend on the surface condition, the turbidity of the water and the diver's depth. A rough approximation of ambient light levels is shown for coastal oceanic water, Figure C.2, and for harbor/bay water, Figure C.3 (Vaughan and Williams, 1976).

Step 2: Calculate display luminance required at the diver's eyes

The target value of luminance at the eye is calculated from the formula

$$CR = \frac{L_E - L_B}{L_B}$$

where:

CR = .40 or .20 depending on ambient light level

L_E = Luminance required at the eye

L_B = Luminance in the ambient water

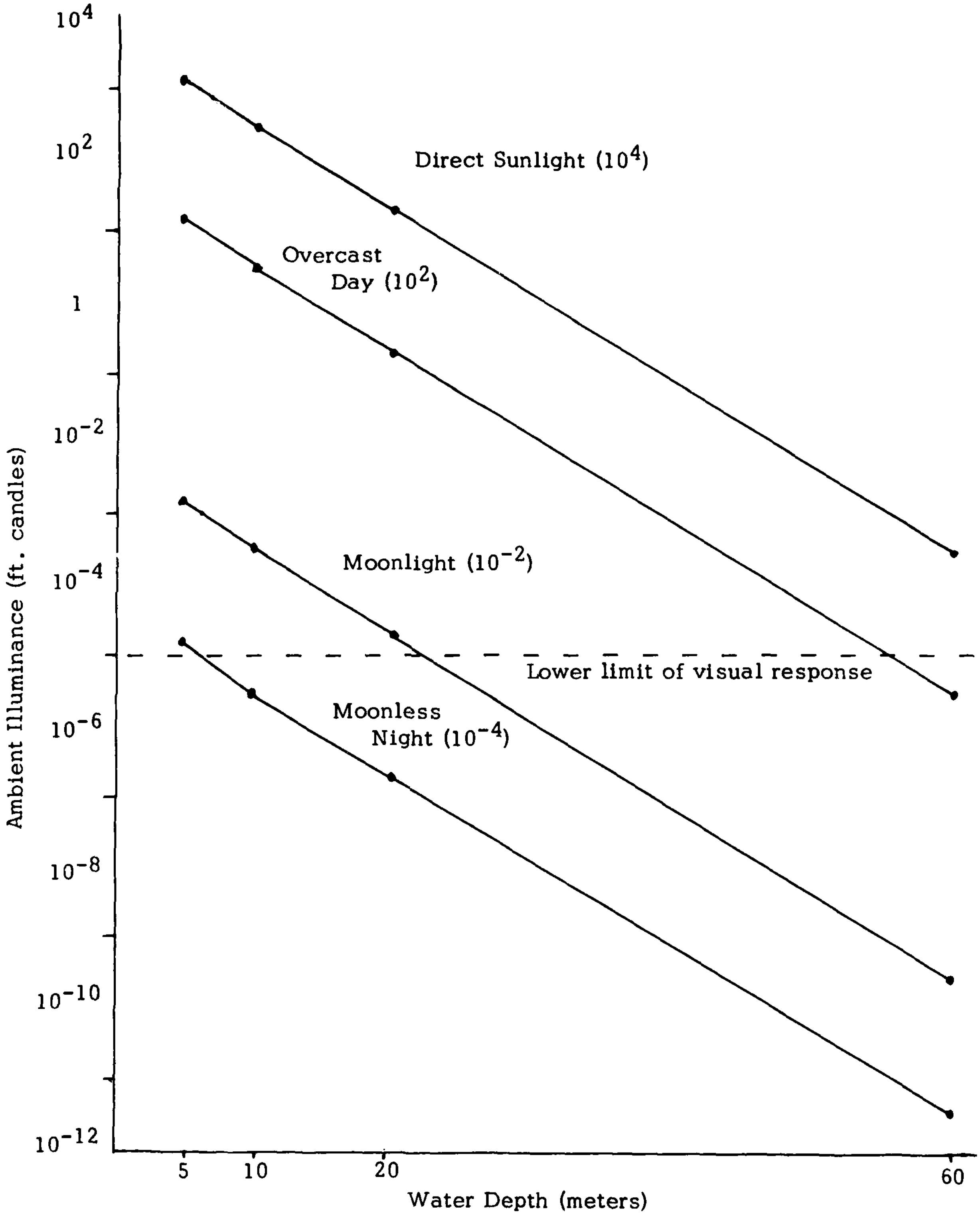

Figure C.2. Ambient Illuminance At Operational Depths in Ocean Water for Various Levels of Surface Illuminance (from Vaughan and Williams, 1976)

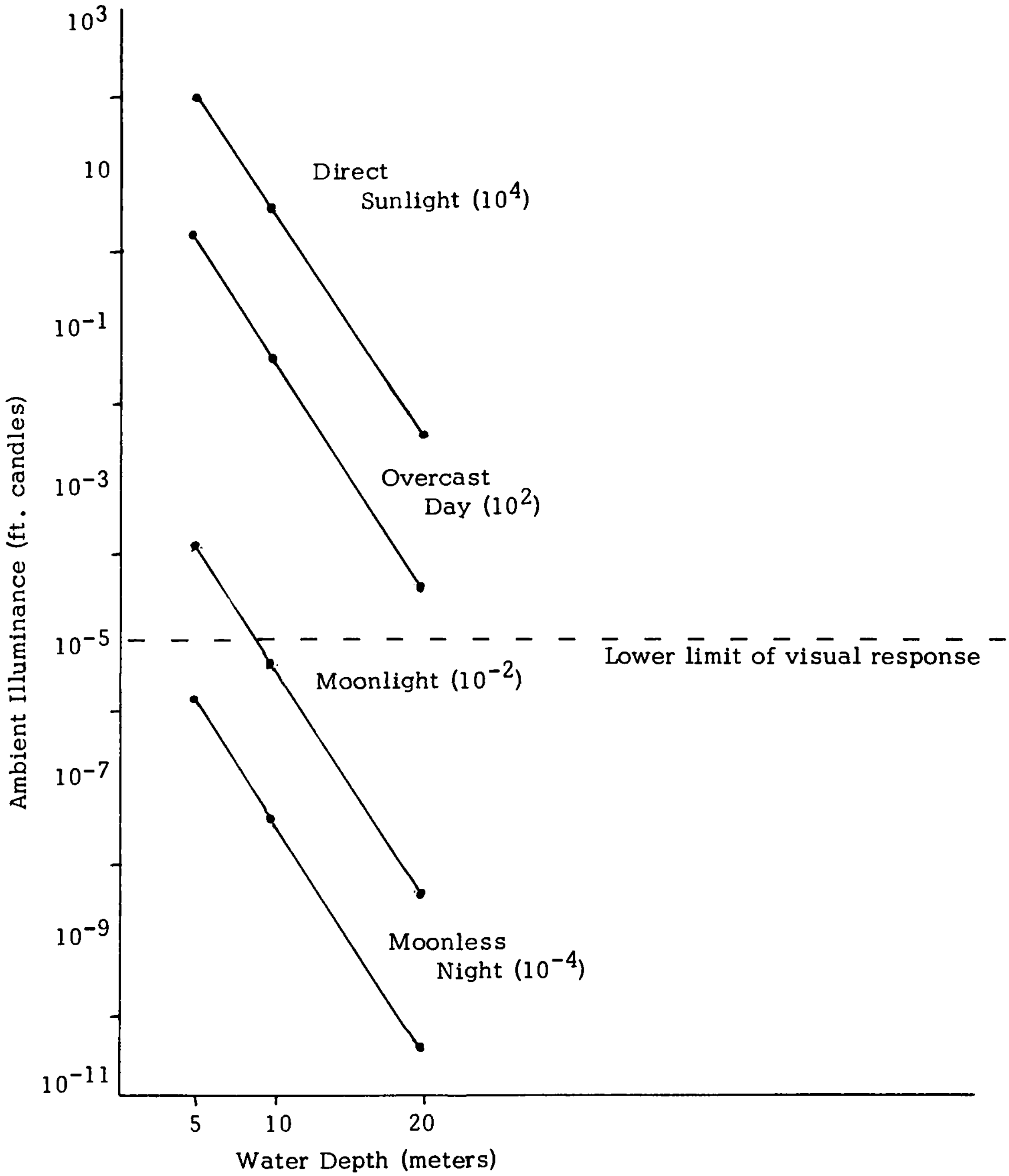

Figure C. 3. Ambient Illuminance At Operational Depths in Harbor Water for Various Levels of Surface Illuminance (from Vaughan and Williams, 1976)

An example of formula application where ambient light is 3.4 cd/m^2 is as follows:

$$.40 = \frac{L_E - 3.4}{3.4}$$

$$L_E = (.40 \times 3.4) + 3.4$$

$$L_E = 4.76$$

Step 3:

Continue with steps 3 and 4 from Case A.

Table C.5 illustrates the application of Case B for four ambient light levels in four types of water.

Table C.5. Amounts of Luminance (cd/m^2) Required for Clear Legibility in Illuminated Water

Ambient Water Luminance	Luminance Required at the Eye for Clear Legibility	Luminance Required at the Display Source for White Light at 14 Inches Viewing Distance			
		Open Ocean T = .97	Coastal Ocean T = .70	Bay T = .42	Harbor T = .004
3.4 cd/m^2	4.8	5.0	7.0	12.0	1,200
34	48	50	70	120	12,000
340	410	423	586	976	102,500
3,400	4,100	4,227	5,857	9,762	1.02×10^6

3. References

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2. Vaughan, W. S., Jr., Glass, R. A., and Williams, J. Luminance requirements and color appearances of colored displays in turbid water: I. Dark ambient viewing environments. Annapolis, Md.: Oceanautics, Inc., December 1978.
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4. Vaughan, W. S., Jr., and Williams, J. An analysis of environmental and perceptual determinants of display legibility underwater. Landover, Md.: Oceanautics, Inc., April 1976.

D. Peripheral Location

1. Human Factor Considerations

In addition to normal constraints on peripheral vision in air the utility of the peripheral visual field underwater is affected by three factors: the structural design of the facemask, the distortion of peripheral signals due to refraction at the faceplate, and the increased distance light is required to travel through turbid water from peripheral vs central locations.

2. Review of Research and Analyses

a. Facemask Structure Limits the Peripheral Field. Facemasks vary in physical shape and size of faceplate and in the amount of peripheral rubber that seals the mask to the face. These design characteristics determine the visual field available to the diver, and various mask designs have been assessed by perimetry studies including the standard oval, kidney-shaped, wide-field, full-face and goggle masks (Weltman, et al., 1965; Kinney, et al., 1972; Luria, et al., 1974). Results of these studies are highly consistent and facemask design is clearly a factor in visual field dimensions. Figure D.1 illustrates the visual fields of two common mask types: standard oval and full-face. Both masks provide a larger peripheral field above the horizontal meridian (270°-90°) than below it; the standard oval mask is particularly restrictive in all downward directions relative to the line of sight. The full-face mask, of course, provides the maximum field of view; between 40° and 60° into the visual periphery depending on direction from line of sight.

b. Distortion of the Visual Image Limits the Peripheral Field. Objects viewed underwater are distorted because light rays from the object change velocity and bend when they pass from the water to air at the diver's faceplate. The change in velocity produces distortions in perception of size and/or distance of observed objects. Optical distortions create visual images of objects

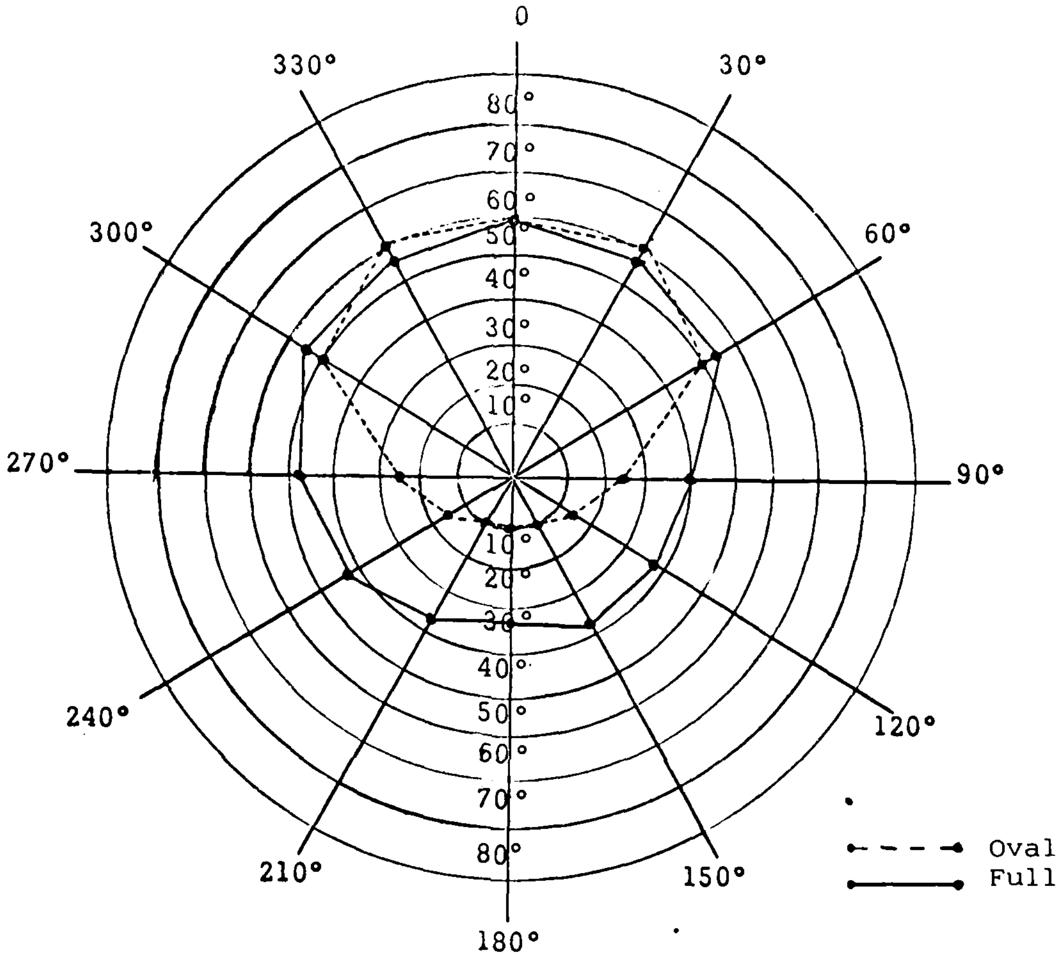

Figure D.1. Visual Fields of Oval and Full Facemasks

which are closer by 3/4 of actual distance and larger by 4/3 of actual size. Because light rays in the periphery are more severely bent than those in the center of the visual field, the distance distortion is exaggerated in the peripheral visual field. Figure D.2 illustrates how light rays are bent at the faceplate and how the location and shape of objects are distorted

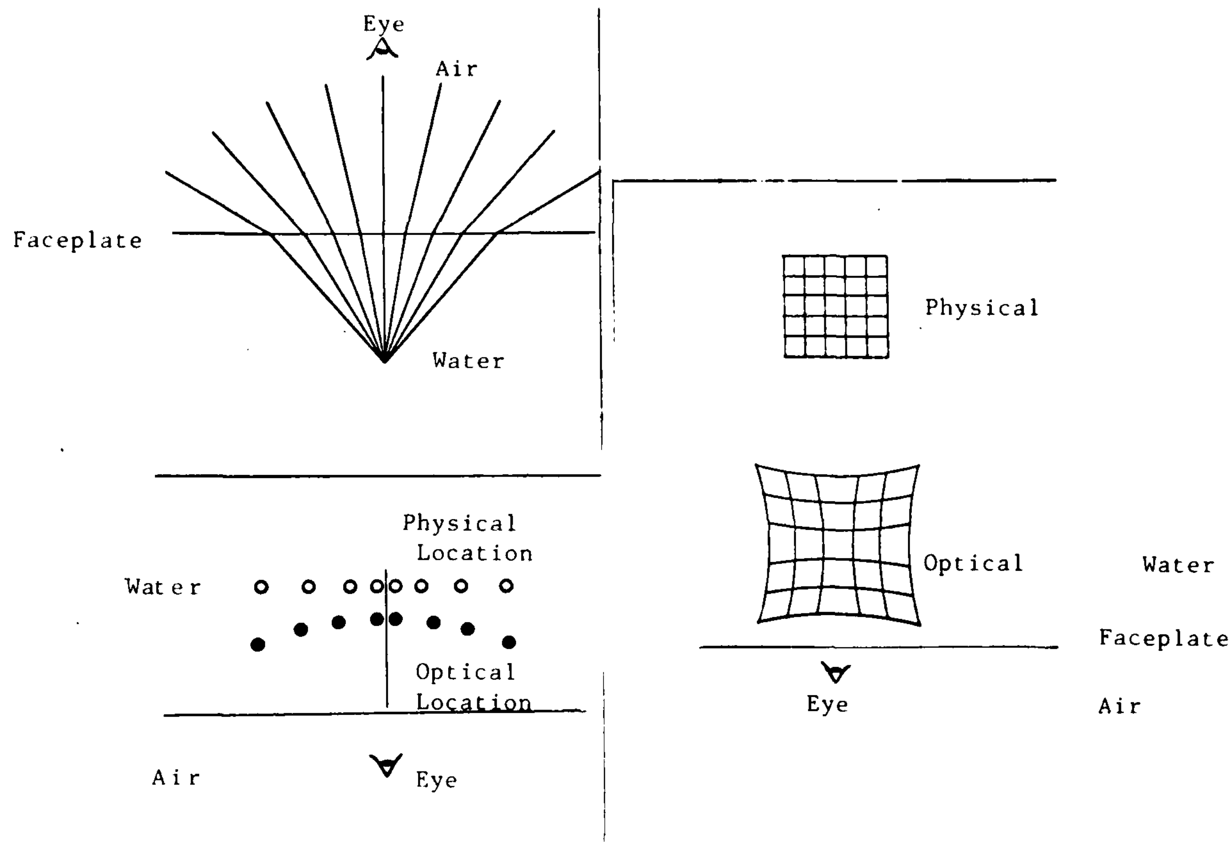

Figure D.2. Illustrations of Refraction of Light
At the Interface Between Air and Water: Light Rays Emanating
from A Point in the Water; and Distortions in the Shape
of Regular Objects Due to Refraction
(from Kinney, et al., 1970)

by optical phenomena. Further, Ross, 1970, has shown that the optical location of peripheral objects is unstable, causing a general blurring in the peripheral visual field. Figure D.3 illustrates this phenomenon.

C. Turbid Water Limits the Peripheral Field. In air environments, peripheral visual signals must be larger or more luminous than those in the central visual field to be equally legible (Grether and Baker, 1972). This is due mainly to the lower sensitivity for small detail of vision in the periphery (where there are many rods and few cones) as compared to the cone-dominated vision of the fovea. Underwater, this phenomenon is aggrevated by severe attenuation of light in highly turbid water and the longer path lengths travelled by peripheral vs central signals. Figure D.4 illustrates reduction in peripheral effectiveness for a reading accuracy task. Differences of only a few inches of pathlength through turbid water had significant effects on the legibility of a digital display of fairly high luminance, 342.6 cd/m^2.

Turbid water also affects peripheral field effectiveness by scattering short wavelength light. Detection tasks are aided significantly by the use of short wavelength (green) light since scattering creates a bloom of light in the periphery while long wavelength (red) light does not. This effect occurs in even the relatively clear coastal oceanic water. Figure D-5 summarizes detection data from both Coastal Ocean and Harbor/Bay viewing environments using peripheral lights at luminances of 0.34 and 342.6 cd/m^2, respectively, and a distance of 14 inches. Reaction time to green light was less than 500 msec to the limit of the experimental condition: 47° into the peripheral field. By contrast, red light could be detected only to a limit of 32° eccentric angle. Visual tasks other than detection do not benefit from scattering by turbid water. Reading accuracy, for example, has been shown to be equally effective in the periphery regardless of display color. Figure D.6 shows reading accuracy at 100% to a limit of 32° into the periphery for both red and green digital displays (Vaughan, Glass and Williams, 1978).

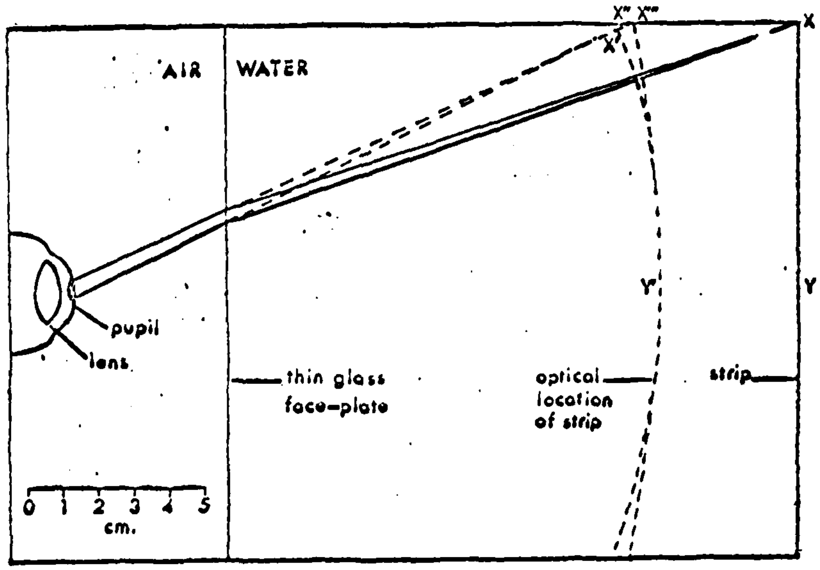

Figure D.3. Optical Distortion of Peripheral Objects Viewed Underwater Through A Facemask (from Ross, 1970)

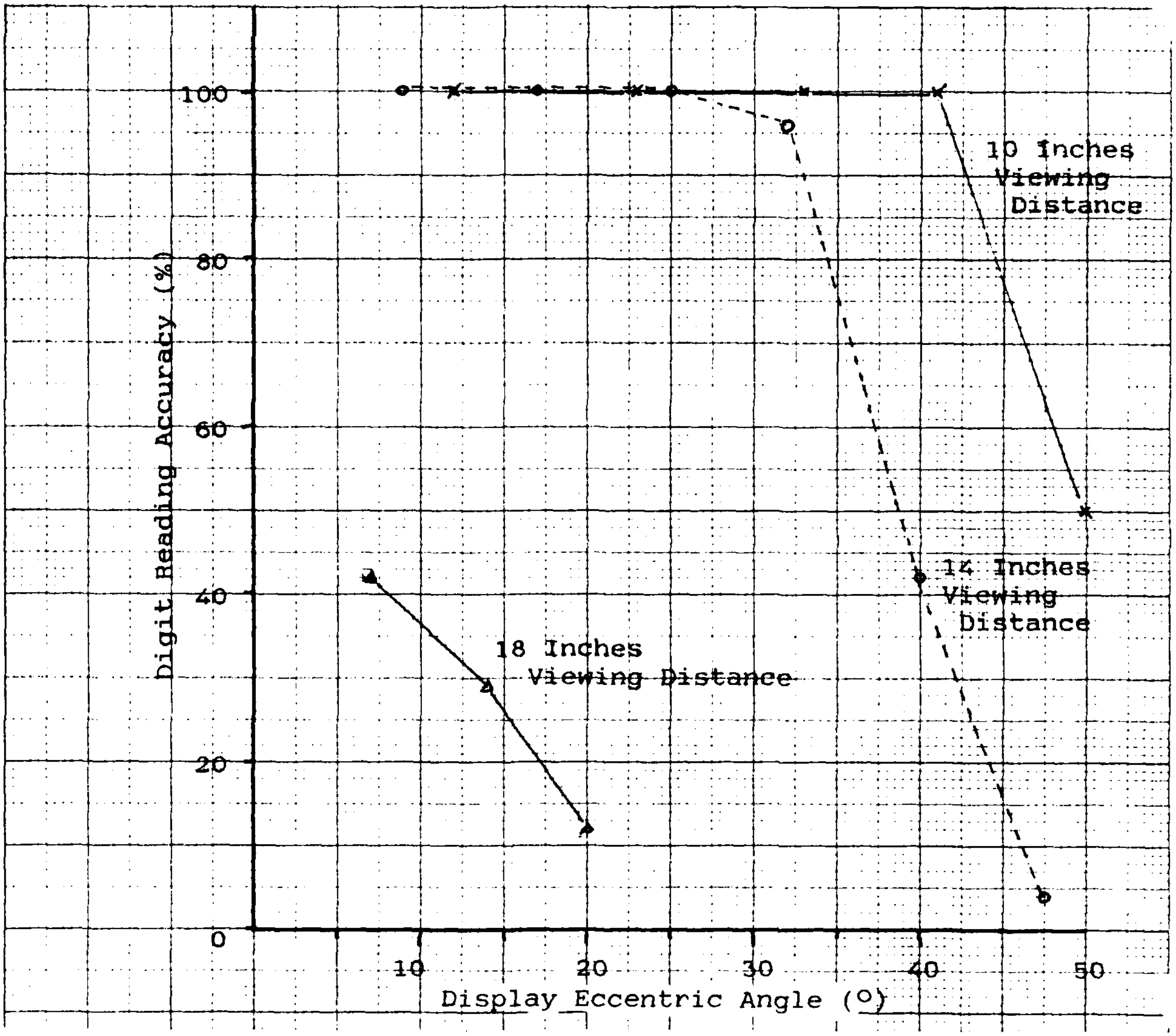

Figure D.4. Identification Accuracy (%) for Digital Displays At 342.6 cd/m^2 When Viewed At A Series of Eccentric Angles from Three Distances: Harbor/Bay Turbidity. (from Vaughan, Glass and Williams, 1978)

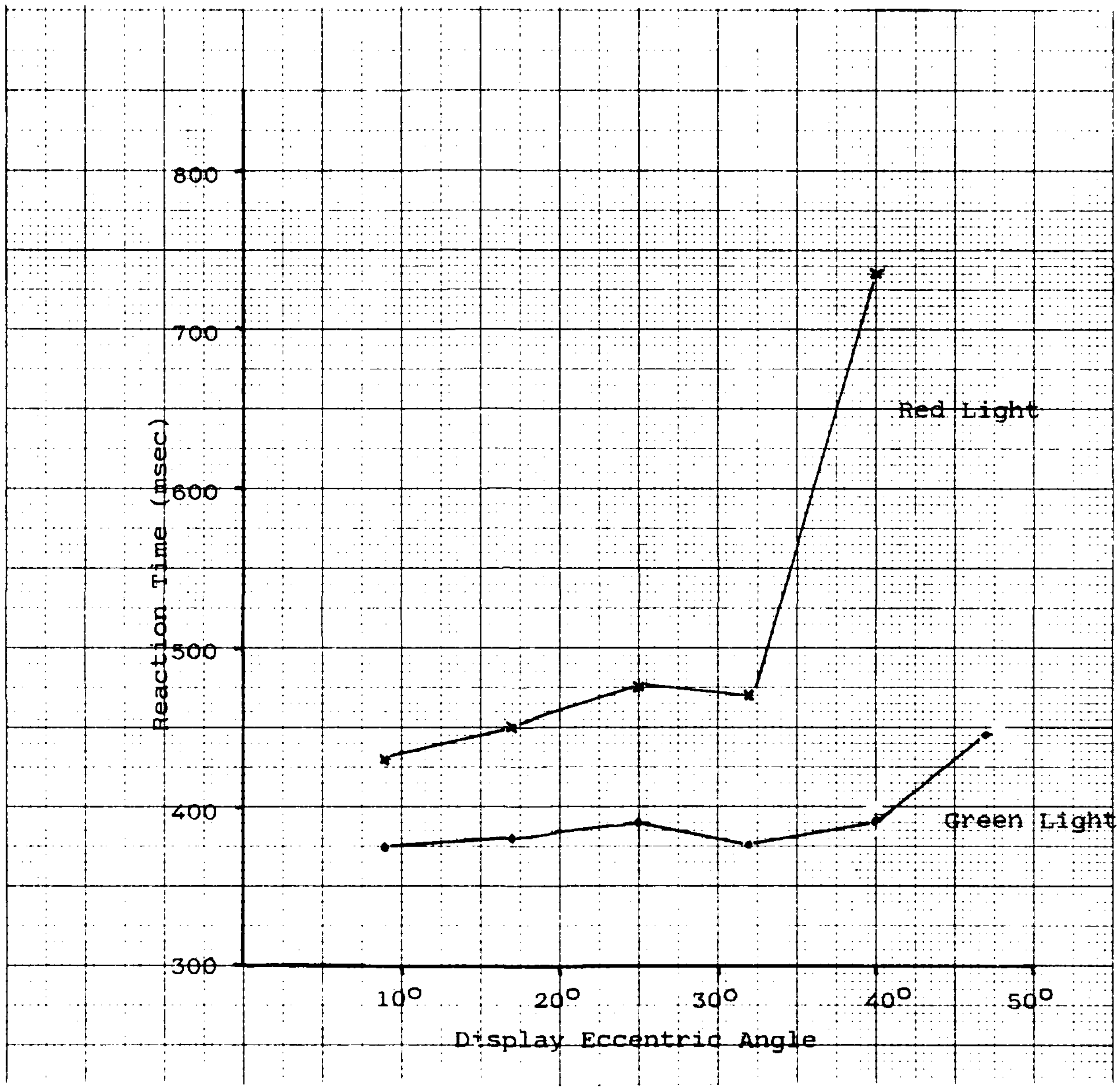

Figure D.5. Speed of Detecting Peripheral Light Signals in Dark, Turbid Water (from Vaughan, Glass and Williams, 1978)

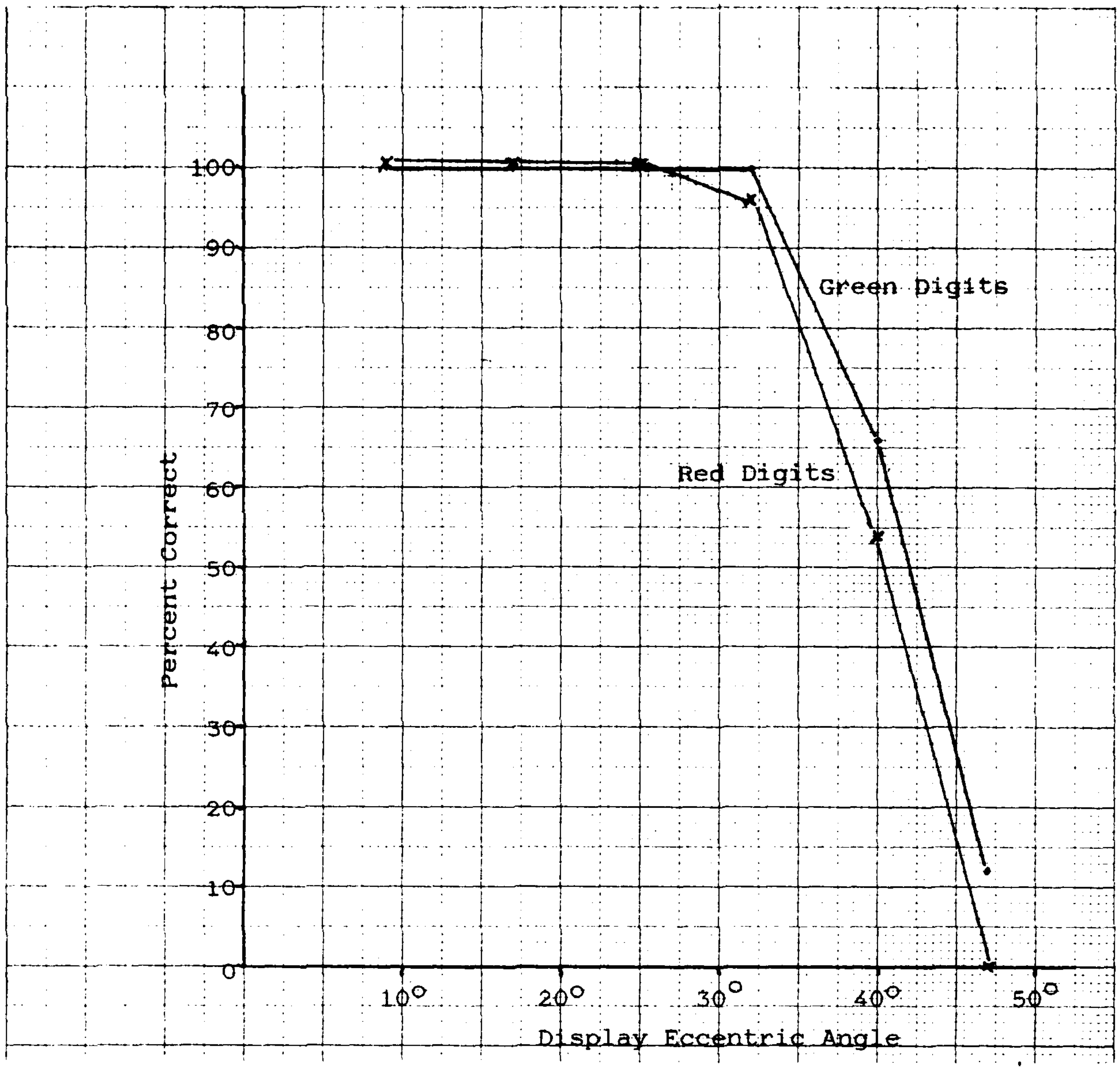

Figure D.6. Accuracy of Reading Peripheral Displays in Dark, Turbid Waters (from Vaughan, Glass and Williams, 1978)

3. References

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E. Use of Color

1. Human Factor Considerations

In air applications color is used as an aid to various visual tasks: e.g., search and detection, identification, classification and sorting, coding common-functions, indicating one or another qualitative state, indicating the steps in a procedural or event sequence, etc. The issues addressed by research on color applications in air include visibility and discriminability, i.e., which colors can be seen best and which subsets of colors are not confused with one another. The available recommendations do not account for two important phenomena in underwater environments; first, that water transmits light selectively according to wavelength (color); and second, that the diver's ambient environment during daylight will tend toward a unique color.

2. Review of Research and Analyses

a. Color As An Aid to Underwater Search and Detection. The color of an underwater object significantly affects its visibility, and the most visible color, i.e., the one which can be seen at longest range, is determined by the turbidity characteristics of the water. Due to the combined effects of absorption and scattering, a given body of water will be maximally transmissive to a narrow band of wavelengths; a long column of water is essentially a monochromator (Tyler, 1959). The wavelength vs transmissivity function is unique to the water sample; but roughly the most transmissive color for typical categories of water is shown in Table E.1.

Table E.1. Maximally Transmissive Colors According to Category of Natural Waters

Water Type	Most Transmissive Color
Clear, Open Oceans	Blue-green
Coastal Oceans	Green
Inshore Rivers, Harbors and Bays	Yellow-Red

Kinney, Luria and Weitzman, 1967, measured the relative visibility of fourteen colors underwater by painting 20 cm diameter spherical floats, attaching the floats to anchors on the bottom of various bodies of water and having divers detect them at maximum range. In natural conditions of illumination, i.e., daylight, the most visible colored floats were predictable from the transmission characteristics of the test sites. Yellows, oranges and reds were best seen in highly turbid river waters; yellows and greens in less turbid sounds and gulfs; blue-green in clear spring waters. Maximum viewing distances for the maximally transmissive colors were approximately 6 ft. in the Thames River, 11 ft. in Long Island Sound, 35-50 ft. in the Gulf of Mexico and 85 ft. in Morrison Springs. Fluorescent paints were more visible than regular paints of the same color. White was the most visible non-fluorescent paint even though the white floats were perceived as the color of the water. Least visible colors in all waters were black and gray. Orange and red were poorly seen in clear water due to absorption; blue and green were poorly seen in highly turbid water due to scattering.

Kinney, Luria and Weitzman, 1969, partially replicated their earlier study under conditions of artificial illumination. All trials were conducted near the bottom of natural bodies of water at night and the colored floats were illuminated with either incandescent tungsten or mercury light sources. Most visible colors under these conditions depended on the wavelengths represented in the light sources as well as the transmission characteristics of the water. Incandescent lamps contain more long-wavelength energy than short; mercury lamps have mostly short-wavelength energy. Consequently, incandescent lamps are good illuminants for yellow, orange and red paints; mercury lamps for yellow-green and green paints.

Kinney and Miller, 1974, extended the general findings about visibility of colors underwater to the Caribbean Sea and added a

caution about the use of fluorescent paints. If their use is contemplated, they must be covered with a protective coating and tests of their underwater durability should be conducted.

Luria and Kinney, 1974, verified the findings of their prior research as applied to a search task in turbid water. Variously painted objects were randomly placed on the bottom, and divers recovered as many objects as they could find in a 15-minute search. In daylight and in turbid water, the most frequently found objects were painted either fluorescent orange or regular white.

Table E.2 summarizes research on visibility of painted objects underwater.

b. Color As An Aid to Display Legibility. In dark, natural waters self-luminous or transilluminated displays will be only slightly affected by the transmission characteristics of the water due to the very short viewing distances involved in reading displays on control consoles, hand-held equipments, etc. An exception is the effectiveness of red light in very turbid water. Vaughan, Glass and Williams, 1978b, determined the luminance required of variously colored displays in order to be clearly legible in highly turbid water. Table E.3 shows the amount of luminance (as measured at the source) needed for six colored and a white display to be seen at two legibility criteria: minimum and clear. The red display (650 nm) required significantlly less source energy than the other colors over a range of display sizes at a 10-inch (25 cm) viewing distance. In Coastal Ocean turbidity the combined effects of scattering and absorption favor the transmission of green light, but those effects are not appreciable over the short pathways involved in console display reading. Table E.4 shows the equivalence of display luminances required for legibility of various wavelengths in coastal ocean turbidity.

Table E.2 The Most Visible Colored Paints for Underwater Search and Detection (Data from Kinney, et al, 1967, 1969 and 1974)

Type of Water	Natural Illumination		Artificial Illumination			
			Incandescent Light		Mercury Light	
	Fluorescent Paint	Regular Paint	Fluorescent Paint	Regular Paint	Fluorescent Paint	Regular Paint
Inshore Rivers, Harbors and Bays: Highly Turbid	Yellow Orange Red	Yellow Orange White	Yellow Orange Red	Yellow Orange Red	Yellow-green Yellow	Yellow White
Coastal Oceans: Moderately Turbid	Green Yellow Yellow-green	White Yellow Green	Yellow Orange Red	Yellow Orange Red	Green Yellow-green Yellow	Yellow White
Open Oceans: Very Clear	Green Blue-green Blue	White Yellow Blue	Green Yellow Orange	Yellow Orange	Green Yellow-green Yellow	Yellow White

Table E.3. Display Luminance (cd/m^2) Required for Minimum and Clear Legibility for Two Display Sizes and for Various Display Colors in Dark, Harbor/Bay Water

Display Wavelength (nm)	Minimum Legibility		Clear Legibility	
	3 mm at 25 cm (41' V.A.)	6 mm at 25 cm (82' V.A.)	3 mm at 25 cm (41' V.A.)	6 mm at 25 cm (82' V.A.)
White	24.26	6.89	143.00	27.75
473	N.D.	8.60	N.D.	N.D.
503	30.01	10.72	N.D.	37.48
552	25.18	7.98	98.87	28.88
579	31.38	7.67	130.63	29.29
608	27.24	7.47	128.65	26.83
640	18.47	7.47	86.27	24.05
$\bar{x}$	26.11	8.11	117.48	29.05

640 nm	18.47	7.47	86.27	24.05
Mean of All Others	27.63	8.22	125.29	30.05

Table E.4. Display Luminance (cd/m^2) Required for Minimum and Clear Legibility for Two Display Sizes and for Various Display Colors in Dark, Coastal Ocean Water

Display Wavelength (nm)	Minimum Legibility		Clear Legibility	
	3 mm at 45 cm (23' V.A.)	3 mm at 25 cm (41' V.A.)	3 mm at 45 cm (23' V.A.)	3 mm at 25 cm (41' V.A.)
White	.55	.27	4.21	1.71
473	.58	.27	6.95	3.80
503	.51	.20	4.21	2.02
552	.48	.20	4.35	1.75
579	.48	.24	4.45	2.95
608	.58	.24	3.08	2.33
640	.65	.31	6.48	2.12
$\bar{x}$	.55	.25	4.82	2.38

In illuminated ambient water, where a diver must read visual displays against a background of relatively monochromatic ambient light, displays whose color is the complement of the ambient color will be most legible. The human visual system includes specialized receptors for color; long exposure to high ambient illumination of a single color 'bleaches' or 'washes out' that color's receptors. The visual system becomes less sensitive to the color of the ambient light (it tends to become a neutral gray) and therefore, relatively more sensitive to its complement since those receptors are still 'fresh'.

Vaughan, Glass and Williams, 1979, collected data on the amounts of luminance required for self-luminous digits to be clearly legible under conditions of monochromatic ambient illumination; a green colored coastal ocean and a yellow colored harbor/bay underwater viewing environments were simulated. Table E.5 shows the superiority of blue-colored digits over all other display colors in a yellow ambient environment. To achieve equivalent legibility, blue displays required less than half the source luminance of other colored displays. This result is even more impressive when viewed in terms of luminance at the eye rather than display luminance. A 25 cm path of harbor/bay water may transmit three times as much red energy as blue. Despite the fact that the long wavelength light (red) is much brighter at the eye, the short wavelength (blue) is the more legible.

c. Color As An Aid to Detection of Peripheral Signals.

In dark, turbid-water viewing environments, red light is most transmissive because the long wavelengths are not so scattered or absorbed by suspended particles; consequently, for most applications red light is the preferred choice. An exception is the detection of a signal light in the periphery of the visual field. In this application the shorter wavelength light, blue-green and green, is superior to the longer wavelengths because the scattering

Table E.5. Display Luminance (cd/m^2) Required for Minimum and Clear Legibility for Two Display Sizes and Various Display Colors in Harbor/Bay Water Illuminated with 214 ft.C of Yellow Light

Display Wavelength (nm)	Minimum Legibility		Clear Legibility	
	3 mm at 25 cm (41' V.A.)	6 mm at 25 cm (82' V.A.)	3 mm at 25 cm (41' V.A.)	6 mm at 25 cm (82' V.A.)
White	9209 cd/m^2	3710 cd/m^2	30426 cd/m^2	10223 cd/m^2
473	5153	2172	N.D.	6938
503	14307	5858	29789	18004
552	16095	6239	40273	18891
579	12077	5715	30197	14262
608	10487	5506	26390	14944
640	10264	3827	29371	9812
$\bar{x}$	11085	4718	31074	13296

473 nm	5153	2172		6938
Mean of All Others	12073	5142		14356

phenomenon creates a bloom of light in the visual field which is reliably and quickly detected. Signal lights of equivalent source energy can be placed much further into the visual periphery if they are green than if they are red, and their onset will be detected well within 500 msec to the peripheral limit of the facemask: approximately 50^{o} from line-of-sight.

Vaughan, Glass and Williams, 1978a, compared the peripheral effectiveness of red and green signals as warning lights in turbid water characteristic of coastal ocean and harbor/bay waters. The colors were of equal luminance and adequate for visibility according to the turbidity condition: 342.6 cd/m^2 in the harbor water and .34 cd/m^2 in the coastal ocean. Their results are summarized in Tables E.6 and E.7. The data in the tables show that green light is detected further into the peripheral field than red light of equal luminance; that the effectiveness of green light remains high as viewing distance increases from 10 to 18 inches while for red light the useful peripheral field shrinks with distance; reaction time to green light is always faster than to red light, and the superiority of green light in speed of response to peripheral signals increases with viewing distance.

d. Color As A Coding Technique. Color is often used as an aid to the identification of common-function displays; to indicate a qualitative condition of a variable; to indicate the stages of an event sequence or the steps in a procedure. In air applications, the main problems with color coding are to achieve equivalent brightness of the variously-colored displays and to insure their discriminability. Underwater, these two issues are complicated by the wavelength-selective transmission characteristic of natural waters. Because of this feature of underwater viewing, selection of display colors must account for the different amounts of energy arriving at the eye for different wavelengths in different waters, and for perceptual phenomena which affect the color appearance of colored light in different ambient conditions.

Table E.6. Time (msec) to Detect Green vs Red Peripheral Signals of 342.6 cd/m^2 Luminance in Dark, Harbor/Bay Water

Display Eccentric Angle	Display Color		Difference in Favor of Green	Mean Difference
	Green	Red		
At 25 cm (10 inch) Eye-to-Console Distance				
12°	337 msec	358 msec	21	25
23°	388	399	11	
33°	356	385	29	
41°	363	404	41	
50°	377	No response		
At 35 cm (14 inch) Eye-to-Console Distance				
9°	351 msec	436 msec	85	98
17°	379	466	87	
25°	366	490	124	
32°	374	468	94	
40°	402	No response		
47°	410	No response		
At 45 cm (18 inch) Eye-to-Console Distance				
7°	364 msec	614 msec	250	256
14°	379	641	262	
20°	413	No response		
26°	410	No response		
33°	421	No response		
40°	421	No response		

Table E.7. Time (msec) to Detect Green *vs* Red Peripheral Signals of 0.34 cd/m^2 Luminance in Dark, Coastal Ocean Water

Display Eccentric Angle	Display Color		Difference in Favor of Green	Mean Difference
	Green	Red		
At 25 cm (10 inch) Eye-to-Console Distance				
12^o	370 msec	424 msec	54	54
23^o	389	439	50	
33^o	401	428	27	
41^o	395	473	78	
50^o	430	491	61	
At 35 cm (14 inch) Eye-to-Console Distance				
9^o	397	427	30	66
17^o	385	442	57	
25^o	423	444	21	
32^o	377	464	87	
40^o	387	472	85	
47^o	476	592	116	
At 45 cm (18 inch) Eye-to-Console Distance				
7^o	384	462	78	69
14^o	410	483	73	
20^o	422	480	58	
26^o	390	474	84	
33^o	448	475	27	
40^o	430	523	93	

(1) Color Appearance of Painted Objects Underwater. To be seen at all underwater, painted objects must be illuminated either by sunlight or by waterproofed lamps. In natural illumination, the color appearances of painted objects are modified by the spectral composition of the ambient light. Depending on the body of water, sunlight from the surface will be filtered toward a narrow range of wavelengths: blue-green in open oceans, green in coastal oceans, yellow to red in highly turbid inshore waters.

Kinney, Luria and Weitzman, 1967, collected data on color appearance as well as visibility for a range of colored paints in a variety of bodies of water. Their results provide empirical evidence of the predictable color confusions attending conditions where monochromatic light illuminates colored paint. Painted objects, illuminated by monochromatic light will be modified in color appearance toward the hue of the illuminant. White paint will appear the hue of the available illumination and the appearance of all other colors will be shifted in the direct of the ambient color. For example, in a turbid harbor the ambient light will be reddish. Consequently, white paint will appear red and other colored paints will shift toward red. Blue will appear green, green will appear yellow, yellow will appear orange, orange will appear red, and red will appear very red.

In a coastal ocean where the ambient light is mostly green, white paint will appear greenish and the color appearance of all other colors will be shifted toward the green end of the color spectrum; just the reverse of the description given above for harbor waters. Illuminated by green light, the color appearance of red paint will shift toward orange, orange toward yellow, yellow toward green; green paint will be very green, and blue paint will appear to be a greenish-blue.

(2) Color Appearance of Self-Luminous or Transilluminated Displays Underwater. While painted objects require illumination from either natural or artificial sources in order to be visible, self-luminous or transilluminated displays provide their own visible energy; and, in dark water, colored lights will appear very close to their natural appearances in air. The viewing distances are short and the display luminances sufficiently high for the light to reach the divers' eyes spectrally intact.

In illuminated waters, the color appearances of self-luminous displays are modified by perceptual processes, and the effects are different from those described for paints. While the appearances of painted objects are modified toward the color of the ambient light, self-luminous displays appear modified toward the complement of the color of the ambient light. Because ambient light underwater tends to be monochromatic a diver's eyes adapt to the ambient color, i.e., their visual-perceptual processes gradually shift the color of the ambient water toward a neutral gray and other colored objects in the environment are modified by the addition of a hue which is the complement of the ambient color. Thus, Kinney and Cooper, 1967, could report SEALAB divers 'seeing' red objects at a depth of 200 ft. in the ocean, a depth where no red energy would be present, having been absorbed totally at much shallower depths. Having adapted to a greenish ambient light, they 'saw' its complement, red.

Vaughan, Glass and Williams, 1979, examined color appearances of six colored displays and a white lighted display in underwater viewing conditions representative of a green-colored coastal ocean and a yellow-colored harbor/bay. At luminances sufficiently high for the display to be clearly legible, color appearances were modified according to predictions from the perceptual phenomenon of chromatic adaptation. In the green environment, divers adapted to green light, green displays appeared white, and the complement of green (i.e., red) was perceptually added to all other

colored lights so that a white light appeared red and all colored displays of a wavelength 579nm or greater appeared red.

In the yellow environment of the harbor/bay, yellow became neutral and the complement of yellow (i.e., blue) was perceptually added to other displays. The white display appeared blue and colored displays of a wavelength of 503 nm or less appeared blue. Table E.8 is a summary of the color names typically given to six wavelengths and a white self-luminous display under the various environmental condition studied by Vaughan, Glass and Williams, 1978b and 1979.

Table E.8. Color Appearances of Self-Luminous Colored Displays in Different Environments

Display Wavelength (nm)	As Seen in Air	In Dark Water		In Illuminated Water	
		Coastal Ocean	Harbor/Bay	Coastal Ocean	Harbor/Bay
473	BLUE	BLUE	BLUE	BLUE	BLUE
503	GREEN	GREEN-blue	GREEN-blue	BLUE	BLUE
552	GREEN-yellow	GREEN-white	GREEN	WHITE	GREEN
579	YELLOW	YELLOW-white	YELLOW	RED-white	WHITE
608	RED-yellow	RED-white	RED-yellow	RED	RED
640	RED	RED	RED	RED	RED
ALL	WHITE	WHITE-yellow	YELLOW-white	RED-white	BLUE-white

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